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Final Technical Report

North Texas Earthquake Studies and Network Operations

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Abstract

The 2016 USGS One-Year Seismic Hazard Forecast for the Central and Eastern US shows increased hazard for North Texas, including the Dallas-Fort Worth Metroplex, due primarily to a series of induced earthquakes occurring since 2008. Under G15AC00141, SMU deployed and/or operated a 30+ station seismic network, hereafter the North Texas Seismic Network, to monitor and conduct research related to the ongoing seismic sequences within the Fort Worth Basin (Azle-Reno, Irving-Dallas and Venus-Johnson County). This report summarizes efforts and data analyses undertaken during the reporting period, May 18, 2015 through June 30, 2016. Network operations included 1) maintaining existing monitoring in Azle and Irving around active earthquake sequences, 2) deploying and maintaining seismic stations to monitor the 2015 M4.0 Venus earthquake sequence, 3) providing unrestricted raw continuous data to the Incorporated Research Institutions in Seismology (IRIS) Data Management Center (DMC) in near real-time, 4) providing earthquake relocations for events within the local networks to the USGS and other collaborators. Research efforts reported herein integrate geologic and seismologic information into geologic subsurface maps of the area for investigations into the possible causes of North Texas earthquake sequences. Based in part on results from G15AC00141, we now hypothesize that northeast-southwest (NE-SW) trending basement faults provide pathways for vertically and horizontally enhanced fluid pressure changes due to wastewater injection in the overlying Ellenburger formation. Johnson County, which lies southwest of Dallas County, hosts some of the largest volume injectors in the basin, and NE-SW trending faults imaged by earthquakes, seismic reflection surveys and by regional geophysical datasets (e.g. gravity, magnetics) potentially allow fluid pressures to migrate to the hydrogeologically lower Dallas-Irving area. This hypothesis now remains to be fully tested. Research on North Texas is posed to make significant breakthroughs in understanding the physical mechanisms leading to induced earthquakes. Collaborative efforts are yielding new constraints on subsurface geology and structure and stress orientation that can constrain a range of modeling approaches.

Introduction

Since 2008, the USGS has reported over 200 earthquakes in the Fort Worth (Barnett Shale) Basin, and event size has increased with time (Figure 1). These rate and magnitude increases in Texas (Frohlich et al., 2016) are consistent with the overall increases noted for the Central and Eastern US (e.g., Ellsworth, 2013; Rubinstein and Mahani, 2015). Southern Methodist University (SMU) and collaborators deployed a number of temporary seismic networks (Figure 2), including unique seismic and infrasound datasets, in North Texas that have been used to produce a high-resolution earthquake catalog, constrain fault locations and geometries for pore fluid pressure diffusion models, and develop testable hypotheses and physical mechanisms that link oil and gas activities in the basin to the recent increase in earthquake rate (Frohlich et al., 2010, 2011, 2016; Frohlich, 2012; Justinic et al., 2013; DeShon et al., 2015a; Hornbach et al., 2015, 2016). In addition, SMU obtained and interpreted seismic reflection profiles across the active regions of the basin to integrate source location and mechanism with local and regional fault structures and deformation history. While the earthquakes in North Texas have not exceeded magnitude 4, the 2014 M4.8 Timpson, east Texas, earthquake caused local structural damage (Frohlich et al., 2014; Fan et al., 2016; Shirzaei et al., 2016), and the 2016 M5.8 in Pawnee, OK, is a reminder that much remains to be learned about potentially induced earthquakes and how to accurately assess hazard associated with these events.

The felt ground motions in a major US metropolitan area like Dallas-Fort Worth, combined with the increased earthquake rates and magnitudes across Texas and Oklahoma, have raised significant community and local government concerns about the hazards and risks associated with potentially induced earthquakes. Concerns have been expressed by residents in local town hall meetings packed to capacity (Azle 2014 and Irving 2015), by local government and emergency management organizations, by infrastructure managers, by industry representatives, and by industry regulators. Accompanying the concerns are calls for additional regulation or immediate suspensions of the perceived causes; appointment of a seismologist to the Texas Railroad Commission and changes to permitting rules for wastewater disposal wells; state funding to create a new state-wide Texas Seismic Network (TexNet) and support earthquake research; and formation of the Dallas County Earthquake working group to foster communication between local emergency managers, and federal, state and local scientists and engineers in the North Texas region. The 2016 USGS One-Year Seismic Hazard Forecast for the Central and Eastern US (Peterson et al., 2016) shows increased hazard for North Texas, with a 1-5% chance of experiencing Modified Mercalli Scale VI ground motions over 2016, and this agreement provided the earthquake data and allied research to better constrain the hazard mapping efforts in North Texas.

Five well-studied earthquake sequences in North Texas were recorded using local seismic stations operated by SMU, in part during the duration of the May 2015- June 2016 USGS-SMU Cooperative Agreement: 2008-2009 DFW Airport (Frohlich et al. 2010, 2011; Janska and Eisner, 2012), 2009 Cleburne (Justinic et al., 2013), 2013-2015 Azle-Reno (Hornbach et al., 2015; Phillips et al., 2014), 2014-2016 Irving-Dallas (DeShon et al., 2015b; Quinones et al., 2015), and 2015 Venus (Scales et al., 2015; Lee et al., 2015) sequences. The SMU hypocenter catalog derived using data collected between 2013 – present currently contains over 1500 earthquakes (Figure 2). The high-resolution earthquake locations computed using double-difference (DD) methods are combined with fault plane solutions, information on subsurface geology and fault structure from seismic reflection data (Magnani et al., 2015), well data (Hornbach et al., 2016), and 3D pore pressure modeling to provide further insight into the relationship between fluid migration at depth and modern seismicity in North Texas.

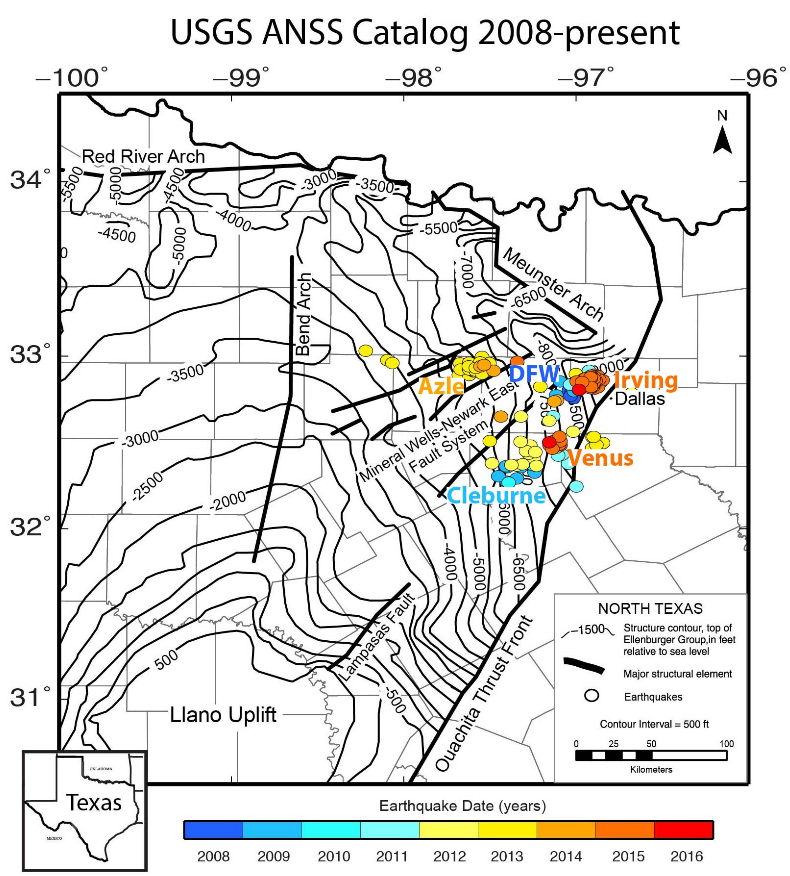

Figure 1. Map of the Bend-Arch Fort Worth Basin showing epicenters reported in the USGS ANSS Catalog 1975-May 2016 (location uncertainty ~5-10 km). Contours indicate the top of the Ellenburger formation, the primary wastewater injection unit of interest, based on Pollastro et al. (2007). The basin depocenter is below the cities of Irving and Dallas in western Dallas County, where a significant increase in seismicity occurred in the past 3 years. Major basement faults trend NE-SW, consistent with fault orientations derived from high-resolution earthquake locations (see Figure 3). Modified from Hornbach et al. (2016).

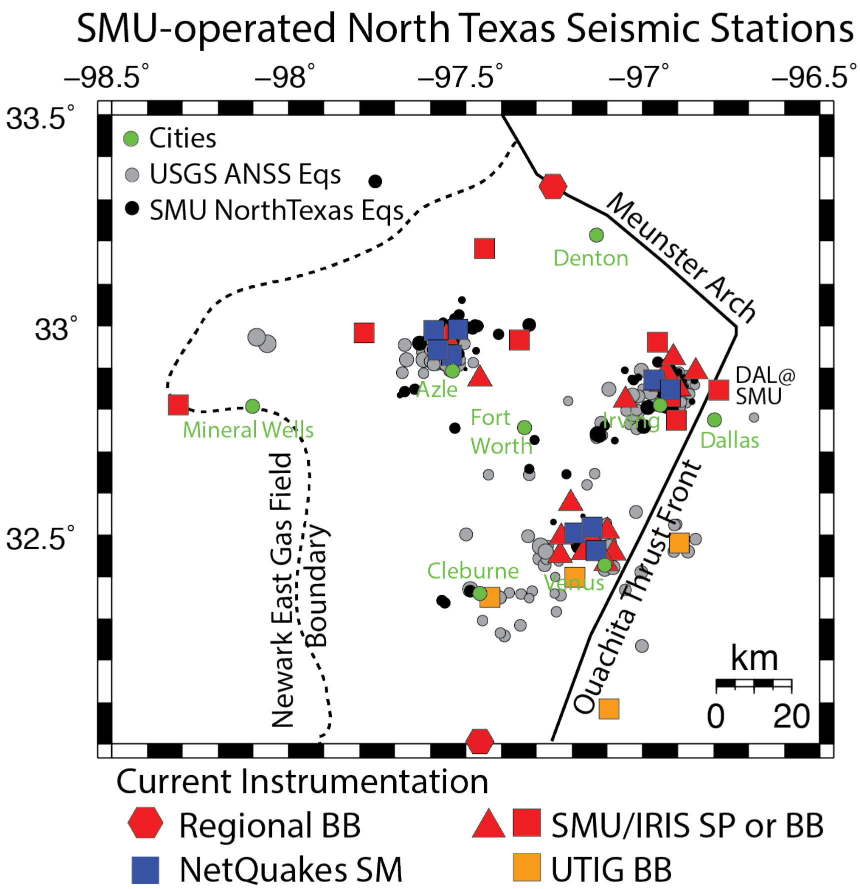

Figure 2. Distribution of seismic stations in North Texas shown with both the USGS ANSS catalog (gray) and the SMU North Texas catalog (black) over the reporting period. In addition to regional broadband stations (red hexagons), SMU operates ~30 stations in collaboration with the USGS, IRIS, and Univ. of Texas Institute for Geophysics (UTIG, J. Walter) (Table 1). The stations are a mix of short-period (triangles), intermediate & broadband (orange and red squares), and NetQuakes accelerometers (blue squares).

Summary of Results

A summary of our results and conclusions to date, partially supported through G15AC00141, and as presented in DeShon et al. (2015b) and Magnani et al. (2015), follows. The sequences can be characterized as swarms in that the first event is not the largest and many of the sequences contain multiple, similar sized earthquakes. Causative faults strike NNE-SSW to NE-SW and are associated with normal faulting (Figure 3). Earthquake depths range from 2.0-8.0 km and are consistent with reactivation of ancient faults located in the Precambrian granites and overlying sedimentary units. The seismically active faults in the basement granites range from 2-6 km in length, dip 40-60° to the SE or NW, extend from ~4-8 km depth below sea level, and are associated with fault areas of 10-15 km^2. Microseismic swarm activity, during which 100s of small earthquakes occur over hours to days during the Azle sequence, appear limited to failure within the Ordovician Ellenburger group, which serves as a wastewater injection unit in the basin and overlies the Precambrian granites. The fault dimensions illuminated by earthquakes are consistent with an intraplate fault system capable of generating high magnitude 4 or low magnitude 5 earthquakes assuming standard earthquake scaling relations (e.g., Wells and Coppersmith, 1994).

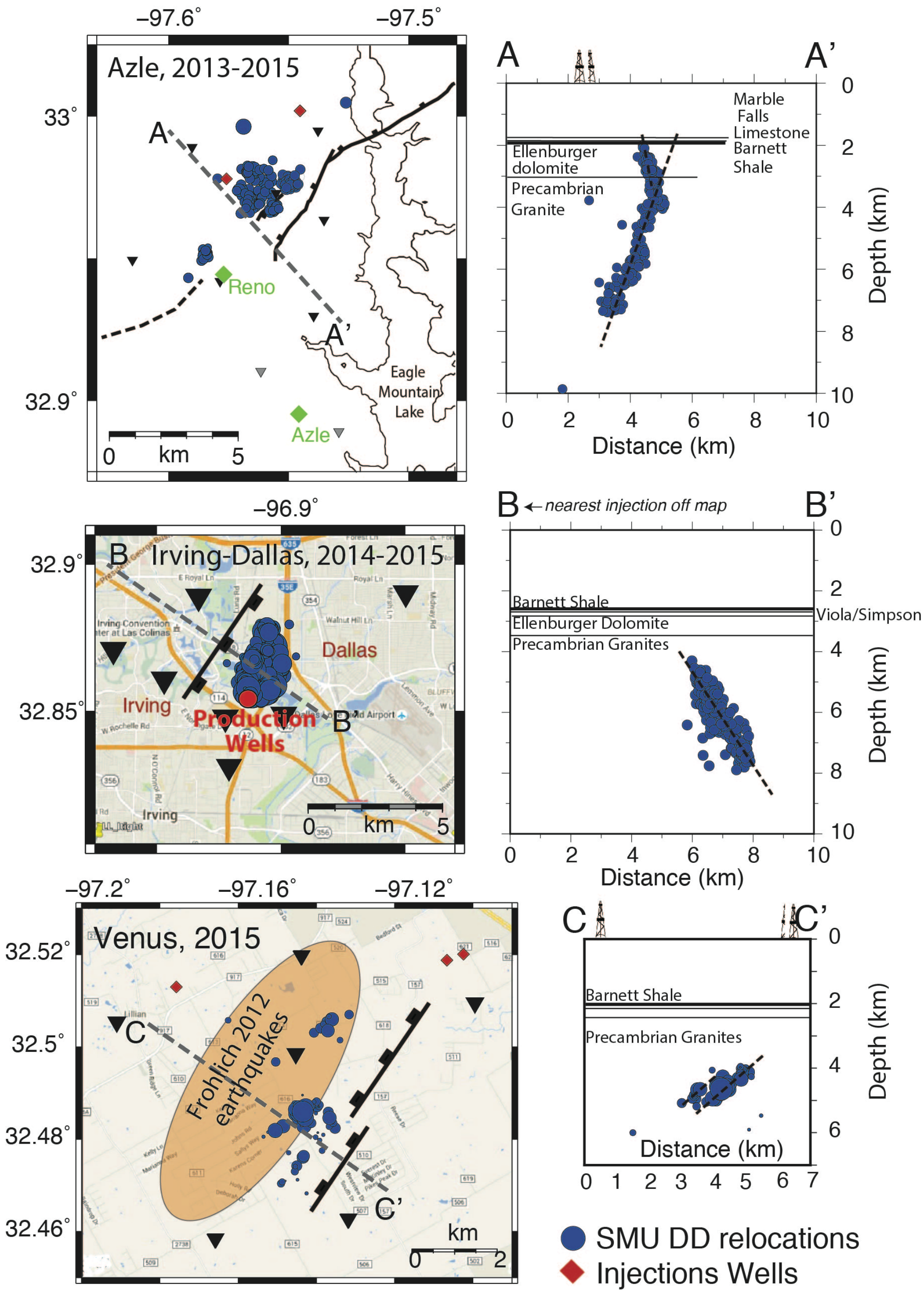

Figure 3. High-resolution double-difference earthquakes locations for the North Texas earthquake catalog, 2013-2015 (DeShon et al., 2015b). All recent North Texas sequences are consistent with normal faulting on NE-SW trending faults in the basement granites. The Azle sequence also contained multiple swarm sequences within the Ellenburger formation.

Hornbach et al. (2016) compile ~10 years of wastewater injection monthly volume and rate data for the Fort Worth Basin and show that earthquakes are spatially associated where cumulative injection volumes, and hence estimated pressure increases, are highest. The Azle sequence has been more directly linked to wastewater injectors located just west and north of the seismic sequence using pressure diffusion modeling (Hornbach et al., 2015) (Figure 3a). The Venus earthquakes are surrounded by large volume injectors located in Johnson County (Figure 3b), and we suggest in a forthcoming paper (Scales et al., in preparation) that the Venus sequence is also linked to wastewater injection. In fact, the
M4.0 Venus sequence appears to occur on a fault illuminated by earthquakes during the passage of the Transportable Array in 2009-2010 (Frohlich, 2012) and imaged by industry seismic data that was procured and analyzed by T. Pratt and M. B. Magnani under G15AC00141. Wastewater injection activities began in Johnson County in late 2006, and the county has hosted felt earthquakes continuously over the basin's Barnett shale gas production history (Figure 1). Barnett gas production, an in particular the issuance of new permits, has dropped in 2016 as commodity prices have been low. Most wastewater in the Fort Worth Basin is flowback water (Hornbach et al., 2016).

What remains an enigma is the physical mechanism(s) leading to the Irving-Dallas sequence (Figure 3b). The nearest wastewater injection well is located ~8 miles to the northwest at the northern edge of DFW airport and is low volume relative to others in the basin, both now and in the past. There is one set of inactive shale gas production wells [API 42-113-30147 and API 42-113-30189] near the southern edge of the Irving earthquake epicenters. The sole producing well ceased production in 2012, and the two wells, drilled off the same pad, are the only known production wells in the region. The wells were by all accounts difficult to drill due to the local geology, which thrusts Ouachita metasediments over the Marble Falls, Barnett, Viola/Simpson and Ellenburger sedimentary units. A publically available fault map provided by XTO Energy shows a number of regional NE-SW striking basement faults that extend into the Ellenburger. These regional faults are located between the airport injector and the Irving earthquakes but have apparently not been reactivated by felt earthquakes. Instead, the Irving sequence appears associated with a fault barely resolved in proprietary industry 3D seismic data collected around nearby production wells and available for interpretation to SMU under the funding of G15AC00141. If the north DFW injection activity and related pressure perturbations are the sole trigger for the Irving-Dallas earthquakes, we cannot explain why similarly oriented faults located between the injector and the earthquakes were not affected by a migrating pressure front moving from west to the east. In Hornbach et al. (2016), we hypothesize instead that the cumulative pressure increase across the basin has been significant enough to trigger earthquakes on faults tens of kms from injection wells. Johnson County, which lies southwest of Dallas County, hosts some of the largest volume injectors in the basin, and we posit that NE-SW trending faults imaged by earthquakes and by regional geophysical datasets (gravity, magnetics, etc.) plausibly allow fluid pressures to migrate more efficiently into to the hydrogeologically lower Dallas-Irving area, assuming the faults are highly permeable (Figure 1). Hornbach et al. (2016) estimate that a permeability of 1-3 $x10^{-13}$ m^2 (100-300 mD) would be necessary for fluid pressures to travel between Johnson County and Dallas over 6 years (2008-2014). Testing of this hypothesis remains to be completed.

Completion of Tasks under G15AC00141

Network Operations and Earthquake Studies

The original North Texas studies of the DFW and Cleburne sequences were conducted using non-telemetered local stations (FDSN code X9) that only remained in place for a few months. The telemetered SMU network (FDSN codes ZW and 4F) developed since 2013 in response to ongoing earthquake sequences, and hence is a complex collection of instrumentation and changing station geometry (Table 1). SMU is currently operating and maintaining more than seven different varieties and mixes of broadband, intermediate, short-period, and strong motion instrumentation in what has become an

~30 station network focused on Azle, Irving/Dallas, and Venus under G15AC00141 (Figure 2). In addition to our traditional network operations, SMU has fielded deployments of exploration-style single channel recorders (Reftek 125 "Texans") to observe the structural response of the Eagle Mountain Lake Dam to Azle earthquakes, to capture the January 2015 portion of the Irving/Dallas sequence, and to record the initial aftershocks of the 2015 Venus sequence. In February 2014, NodalSeismic in cooperation with SMU installed and operated 130 vertical 10 Hz recorders (1component nodes) near the Azle sequence for 10 days. All SMU network data are archived in near real-time with the IRIS DMC and made freely available to the public.

Under G15AC00141, we produced a hypocenter catalog produced using 1D velocity models designed for each earthquake sequence and Richter magnitude estimates. This catalog has been widely shared with collaborators interested in induced earthquakes and a publication outlining the network operations and catalogs is planned (DeShon, Hayward et al., planned). Earthquakes are identified using autodetection approaches but due to the high noise metropolitan environment, waveforms are also manually reviewed. Earthquakes are located using *GENLOC*, a flexible implementation of the Gauss-Newton inversion method applied to single event location (Pavlis et al., 2004) and layered 1D velocity models developed for each sequence based on sonic log information or published 1D models. We have additionally computed focal mechanisms using P first motions in HASH (Hardebeck and Shearer 2002) and many mechanisms are consistent with normal faulting. Mechanism quality over the reporting period ranges from B (RMS fault plane uncertainty ≤35°) to D (maximum azimuthal gap ≤ 90°, maximum takeoff angle gap ≤ 60°) due to the limited number of stations and high urban noise levels. Efforts to improve the focal mechanisms using S/P amplitude ratios are continuing. Some examples of North Texas quality B and C focal mechanisms using only P-waves are show in Figure 4. We cross-correlate earthquake waveforms using the GISMO suite (Buurman and West, 2010) and use the resulting differential times for DD location (Waldhauser and Ellsworth, 2000) and tomography work (Zhang and Thurber, 2003). The resulting correlated stacks are used for composite P-wave mechanisms that have RMS fault plane uncertainties of ≤25° (Figure 4). During the reporting period, we began stress drop studies of Azle earthquakes using Brune source modeling. We have since expanded the work to include all North Texas earthquakes and explore other methodologies, and the results are expected to be published in 2017 by S. Jeong, B. Stump and others.

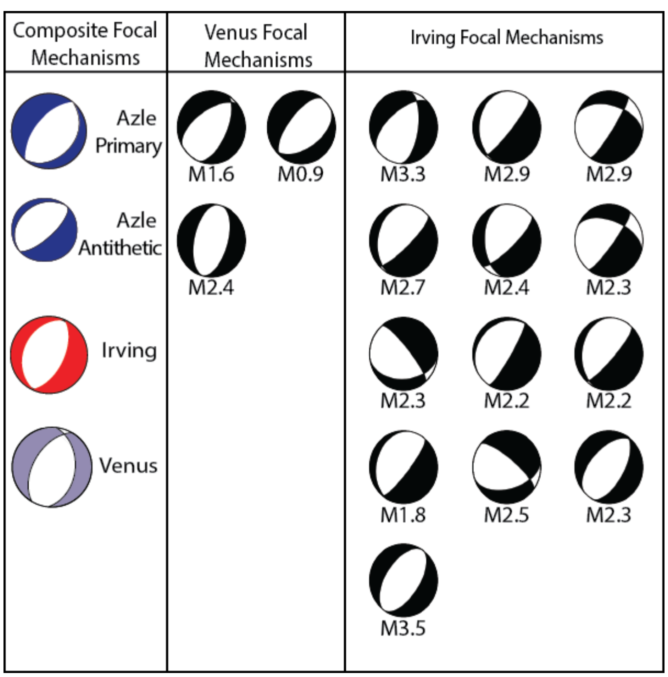

Figure 4. P-wave first motion focal mechanisms for North Texas. Mechanisms are calculated within HASH (Hardebeck and Shearer, 2002), which allows for use of multiple velocity models to compute take-off angles and provides statistical measures of solution quality. Mechanisms show here have an RMS fault plane uncertainity of ≤45° (quality A-C). Due to station distribution changes over time and the small magnitude of events recorded in Azle, no individual Azle earthquake has a computed focal mechanism of quality A-C. Composite focal mechanisms are calculated using the first motion of the stacked, correlated waveforms for each sequence.

Table 1: North Texas Seismic Network (SMU, USGS, IRIS, UTIG)

Station	Instrument Type/Owner	Communication	Location	OnDate
Azle Swarm (multiple M3.5+)				
AZHS	USGS NetQuake	Local Wifi	School	2013348
AZNH	USGS NetQuake	Local Wifi	Church	2013358
RESD	USGS NetQuake	Local Wifi	School	2013347
BVFD	USGS NetQuake	Local Wifi	Firestation	2015084
EML1	SMU 4.5Hz + IRIS 2Hz	IRIS Cell	Dam	
AZCF	IRIS BB	IRIS Cell	Church	
AZHL	AFTAC CMG6T	IRIS Cell	City	
AZWR	AFTAC CMG6T	IRIS Cell	Boy Scouts	
AZWP	AFTAC CMG6T	IRIS Cell	City	
AZDA	SMU/4.5Hz 1 Hz	Local WiFi	Home	
Irving/Dallas swarm (multiple M3.5+)				
UDFD	USGS NetQuake	Local Wifi	College	2015012
NLKCP	USGS NetQuake	Local Wifi	College	2015009
IFS3	IRIS BB	Irving WiFi	Firestation	2015007
IFBF	IRIS 4.5Hz	Irving WiFi	Firestation	2015026
ITL1	IRIS 4.5 Hz	Irving WiFi	Levee	2015026
ITSC	IRIS 4.5Hz	Irving WiFi	Home	2015011
ILCC	IRIS 4.5Hz	Irving WiFi	Business	2015051
AFDA	IRIS 4.5Hz	Irving WiFi	Business	2014329
IPD1	IRIS Accel + SMU/AFTAC 2Hz sensors	Irving WiFi	Police Station	2015005
IFCF	IRIS BB	Irving WiFi	Firestation	2015042
IFDF	IRIS BB	Irving WiFi	Firestation	2015032
IFCF	IRIS BB	Irving WiFi	Firestation	2015042
IFDF	IRIS BB	Irving WiFi	Firestation	2015032
Venus M4 event				
VLBC	USGS NetQuake	Local Wifi	Church	2015132
VMTW	USGS NetQuake	Local Wifi	Home	2015132
VTAX	USGS NetQuake	Local Wifi	Business	2015132
VPCK	IRIS 4.5Hz	IRIS Cell	Home	2015139
V2600	IRIS 4.5Hz	IRIS Cell	Home	2015139
VVFD	IRIS 4.5Hz	IRIS Cell	Firestation	2015139
VBMS	IRIS 4.5Hz	IRIS Cell	Home	2015139
VBB1	IRIS 2Hz -> 4.5Hz in 2016	IRIS Cell	Home	2015142
VMCM	IRIS 2Hz -> 4.5Hz in 2016	IRIS Cell	Home	2015142
VNLC	IRIS 2Hz -> 4.5Hz in 2016	IRIS Cell	Home	2015142
VSAB	IRIS 2Hz -> 4.5Hz in 2016	IRIS Cell	Home	2015142

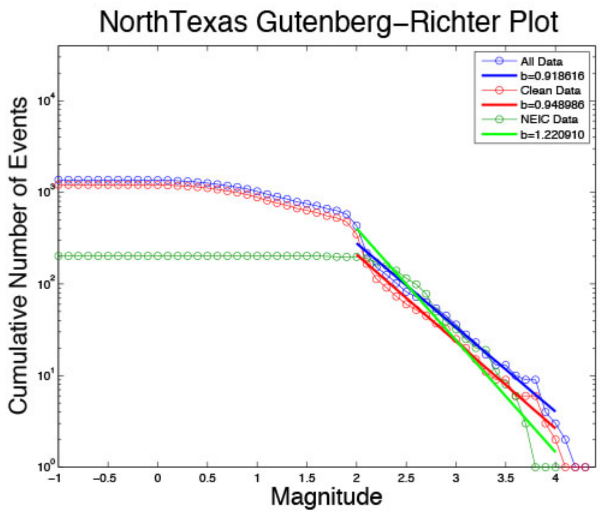

Figure 5. Preliminary Gutenburg-Richter plots for the SMU and the ANSS (NEIC) catalogs for North Texas earthquakes through May 2016. All SMU data (blue) and low uncertainty (aka "clean") data yield b-values of ~0.95. The ANSS value of ~1 is highly dependent on choice of completeness and only uses 201 events. Note that the SMU catalog used in this plot calculated Richter local magnitudes.

In all North Texas cases, hypocenter locations based upon regional network locations and reported in the USGS ANSS catalog, have been useful to indicate that a new sequence had started at M2.5+, but have not been sufficiently accurate to image the active portion of the fault, to associate the seismic activity with industry seismic reflection data (including in some cases 3D seismic surveys), or in some cases to even suggest which of several Class II wastewater disposal wells should be further investigated. SMU network data is used by the USGS, and magnitude completeness of the ANSS catalog appears to have improved to ~M2.5 (Figure 5), down from M3.0 in 2008. Template matching and other advance waveform correlation techniques can provide more accurate event counts below M2.5 (e.g., Skoumal et al., 2014), and hence more accurate b-values, but absolute hypocenter accuracy is lost. We have been working with M. Brudzinski (Miami-Ohio) and J. Walter (UTIG) on this issue using DD techniques with template matched differential times under NEHRP funding to Brudzinski and TexNet funding to Walter.

Fault Studies

In addition to the efforts related to constraining the location and character of the emerging seismicity in the North Texas basin, the under G15AC00141 agreement the SMU team continued its efforts to build a subsurface structural model of the basin based on well, seismic reflection and potential field data. Such effort is particularly crucial in regions of potentially induced seismicity where the discrimination between the anthropogenic and the natural seismicity is required to properly assess the seismic hazard (Petersen et al., 2016) and to identify the mitigation policies to implement. This is because most studies addressing the relationship between industry practices and seismicity in intraplate regions like the Fort Worth basin focus predominantly on current seismicity, which provides an a-posteriori assessment of the processes involved. Seismic reflection data, particularly 3D volumes, contribute complementary information on the existence, distribution, orientation and long-term deformation history of faults that can potentially become reactivated by the injection and the stimulation process. These data are therefore critical for further studies that address the potential for reactivation (e.g. Walsh and Zoback, 2015), and that are predicated on the assumption that the location, geometry and character of faults in the subsurface is detectable, resolvable and therefore known.

Under the G15AC00141 agreement SMU was able to procure 31.5 km of 2D seismic reflection data (12.9 km of which reprocessed in 2010 to PSTM levels) through Seismic Exchange, Inc. across the fault system that reactivated during the 2008 Venus seismic sequence in Johnson Co. The seismic reflection data consist of three seismic profiles recorded to a maximum time ranging between 4.4 -7 s (TWTT) located along eastern edge of the basin where the Ouachita tectonic units are thrust over the Fort Worth basin sequences with a west-northwest vergence (Figure 6). The seismic profiles image with continuity the main elements of the basin stratigraphy from the Cretaceous/Paleozoic unconformity, at an approximate depth of .5 s (TWTT), to the top of the Mississippian Barnett Shale Units, at the contact with the Pennsylvanian Marble Falls limestone, at ~1.2 s TWTT, the Viola-Simpson Group, at 1.3 s TWTT, the top of the Ordovician Ellenburger limestone at 1.4 s TWTT. The top of the crystalline basement in contact with the Ellenburger Group is marked by a continuous, strong reflector at about 1.8 s TWTT on all seismic profiles. The crystalline basement appears transparent, with rare, discontinuous reflectors down to the lower limit of the recorded profiles (7 s TWTT).

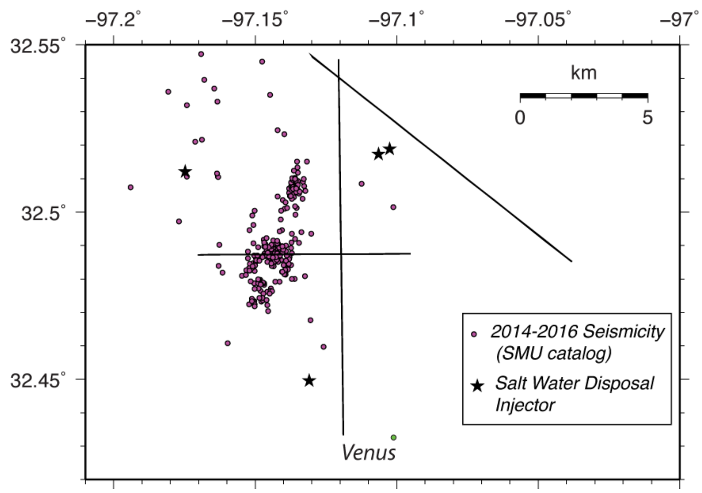

Figure 6. Location of seismic reflection profiles in Johnson County obtained by the USGS as part of the G15AC00141 agreement from SE Inc., analyzed and interpreted by SMU.

The stratigraphy so defined is clearly deformed by faults that offset the Ordovician and Mississippian sequences, with clear displacement of the top of the basement. The Pennsylvanian units above the Marble Falls appear continuous and undeformed. The Ouachita Thrust fault is traceable at the top of the reflection profiles as a east-southeast dipping surface separating well stratified units to the west-northwest from chaotic and featureless units to the east-southeast. The Paleozoic/Cretaceous unconformity is imaged as an undisturbed horizon sealing the underlying deformation at the top.

The integration of the structural interpretation of the seismic profiles with the Venus seismicity shows that the two northwest dipping faults identified by hypocentral locations correspond to two main structural elements deforming the Mississippian, Ordovician and Precambrian sequences, indicating that the 2008 Venus sequence reactivated two pre-existing faults that penetrate the basement and displace the Paleozoic sequences up to the Barnett Shale group. The sequences above the Barnett Shale group are clearly undisturbed and the seismic reflection data resolve no displacement associated with the active faults. This observation suggests that the active fault show no evidence of long-term tectonic activity, but rather that recent seismicity reactivated faults that had been quiescent over a long time. Displacement calculations based on the current seismicity and on the observed deformation support either an exceptionally long return time along these faults (in the order of 150 ka) or a recent rejuvenation of fault activity, likely associated with industry practices in the basin (Magnani et al., 2015; Magnani et al., in prep).

CONCLUSIONS

SMU continues to monitor and conduct studies of North Texas earthquakes using the seismic data collected under G15AC00141. Funding was to initially cover monitoring and study of Azle and Irving earthquakes, in cooperation with the USGS, but enabled SMU to rapidly respond to the May 2016 M4.0 Venus, Johnson County, earthquake as well. SMU has implemented continuous waveform data telemetry and archiving, daily analysis of earthquake waveforms (event-specific analysis upon USGS request), a daily updated hypocenter catalog with local magnitudes, and produced public updates and/or reports in cooperation with USGS Central and Eastern US office. The research networks and standard products will be summarized in a Seismological Research Letters paper in preparation (DeShon, Hayward et al., in prep). Research products include DD earthquake relocations, focal mechanisms, and event similarity determinations for Azle, Irving/Dallas, and Venus (Scales et al., in prep). The three sequences are associated with normal faults striking NNE-SSW to NE-SW and hypocenters generally occur within the Precambrian basement, which is in direct contact with overlying Ellenburger dolomites used an the wasterwater storage interval in the Fort Worth Basin. The exception is the Azle sequence, which also hosted numerous small magnitude earthquakes on an antithetic fault that extended through the Ellenburger (Hornbach et al., 2015). Initial stress drops calculations yield lower values than typical intraplate earthquakes but further work is required to confirm this observation. The fault dimensions illuminated by earthquakes are consistent with an intraplate fault system capable of generating high magnitude 4 or low magnitude 5 earthquakes assuming standard earthquake scaling relations (DeShon et al., 2015b).

Seismic reflection data obtained under G15AC00141 agreement interpreted using coincident and nearby wells to correlate seismic reflection and stratigraphic markers, allow us to identify the faults that ruptured during the 2008 Venus sequence (Scales et al., in prep). The seismic data show that the faults displace the Precambrian basement and the Ordovician Ellenburger Group, throughout the Pennsylvanian Marble Fall Limestone, including the Barnett Shale Group, with little to no deformation of younger sequences. Specifically, any vertical offset in the post-Pennsylvanian formations are below the resolution of the seismic data at these depths (~10 m), far less than expected had these faults accumulated deformation over the long term. Average displacement/sequence derived from cumulative seismic moment calculations for the active sequences indicate that a vertical offset equal to or less than 10 m along the currently active faults implies a minimum average recurrence interval of ~150,000 years. These exceptionally long intervals are at odds with the increasing number of faults reactivated in the North Texas basin since 2008, and suggest that the recent seismicity in the North Texas basin is highly anomalous, and therefore more likely induced than natural (Magnani et al., in prep).

Data Management

All continuous seismic data is archived with the IRIS DMC under FDSN network code 4F (Venus 2015-2016, doi:10.7914/SN/4F_2015) and FDSN network code ZW (Azle & Irving/Dallas 2013-2016, doi:10.7914/SN/ZW_2013). The SMU hypocenter catalog is available upon request until publication in the peer-reviewed literature.

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